Differential absorption radar at 170 GHz for atmospheric boundary layer water vapor profiling

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Scientific motivation

Problem:

- Existing remote sensing platforms have limited ability to retrieve *high-resolution, unbiased* water vapor profiles in the presence of clouds
- Problem recognized by NWP community (WMO, 2018):

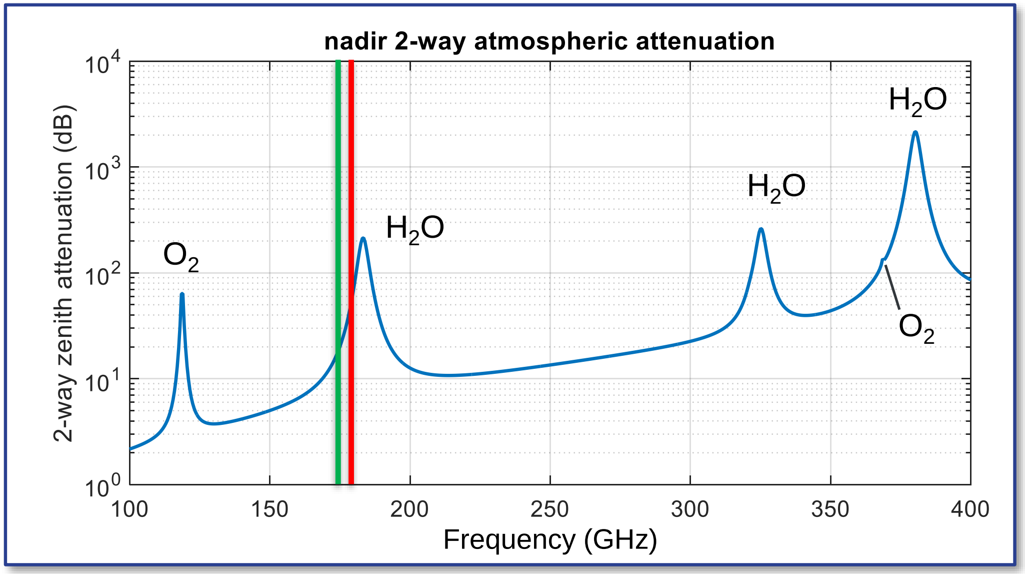
  “Critical atmospheric variables that are **not adequately measured** by current or planned systems are temperature and **humidity profiles** of adequate vertical resolution **in cloudy areas**.”

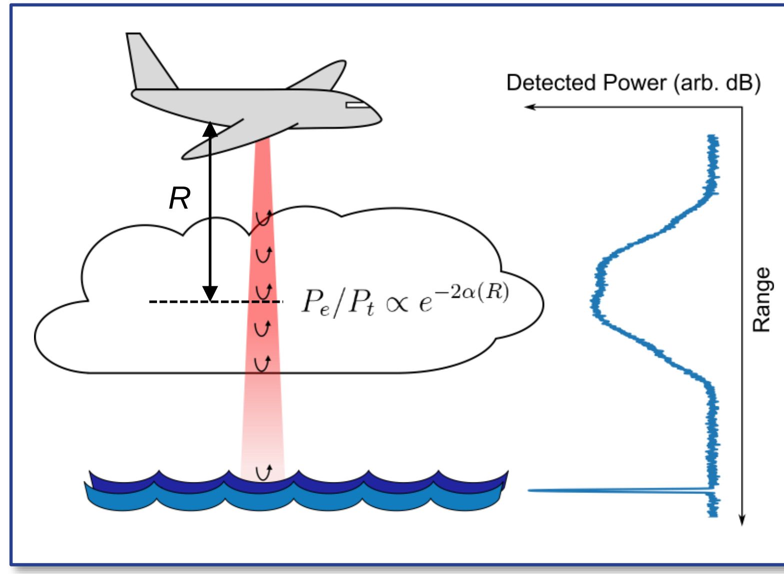
Proposed solution:

- Utilize range-resolved radar signal *and* frequency-dependent attenuation on flank of 183 GHz water vapor absorption line, so-called *differential absorption radar* (DAR)
- Microwave analog of differential absorption lidar (DIAL) – but can measure inside clouds (complementary observations)
- NASA Langley - prototype pressure sounder using O_2 differential absorption, no ranging [1]

[1] Lawrence et al. 2011, doi:10.1016/j.jqsrt.2010.06.001

Measurement basis





- Differential reflectivity between two closely spaced frequencies proportional to absorbing gas density (integrated)

$$\mathrm{dBZ}(r, f_1) - \mathrm{dBZ}(r, f_2) \propto \int_0^r \rho_{\mathrm{gas}}(r')dr'$$

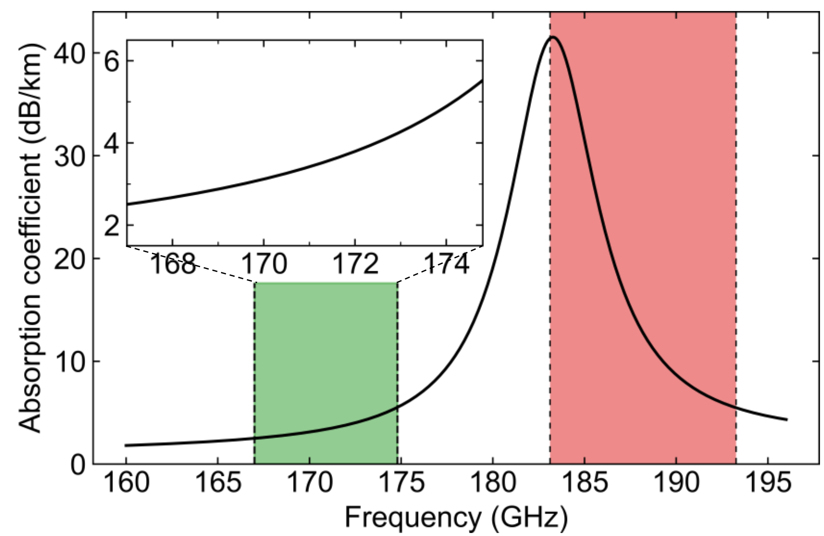
- *Important assumption*: Reflectivity and extinction from hydrometeors independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Airborne platform ⇒ Surface echoes (total column water)

The vapor in-cloud profiling radar (VIPR)

VIPR

- Achievable transmit power < 1 W ⇒ **FMCW mode of operation**
- Tunable across 167 to 174.8 GHz band
- Simultaneous cloud/vapor sounding
- Targets boundary layer clouds/precipitation and total column water vapor
- Demonstration flights on Twin Otter in 2019

VIPR frequency band

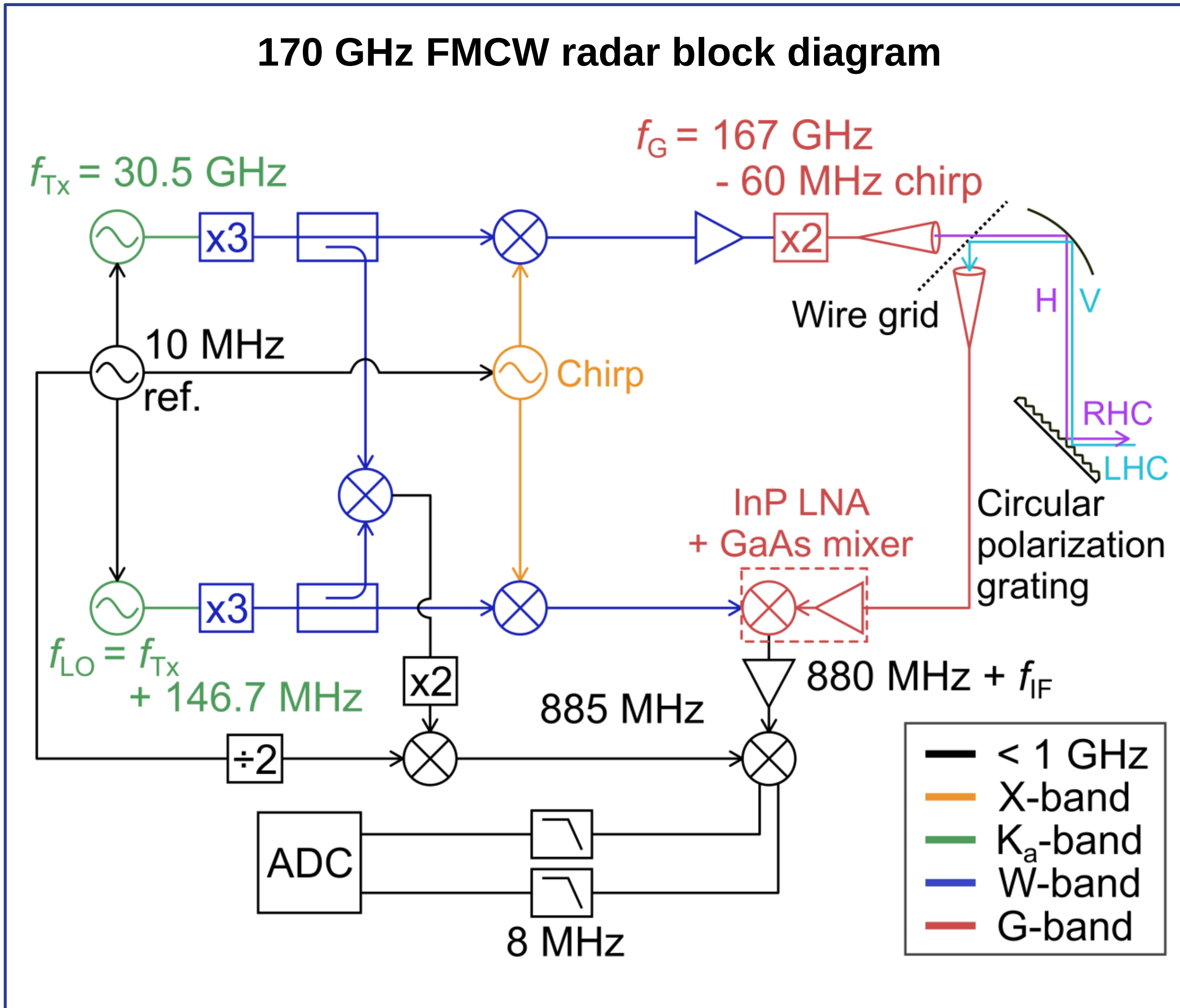


Red band:
- Sensitivity to upper-tropospheric water vapor (ice clouds)
- Strong attenuation in planetary boundary layer (PBL)
- Transmission prohibited (passive sensors)

Green band:
- Lower absolute absorption ⇒ sensitivity to PBL water vapor
- Profiling (PBL clouds/precipitation) and total column water measurement capabilities
- Fewer transmission restrictions

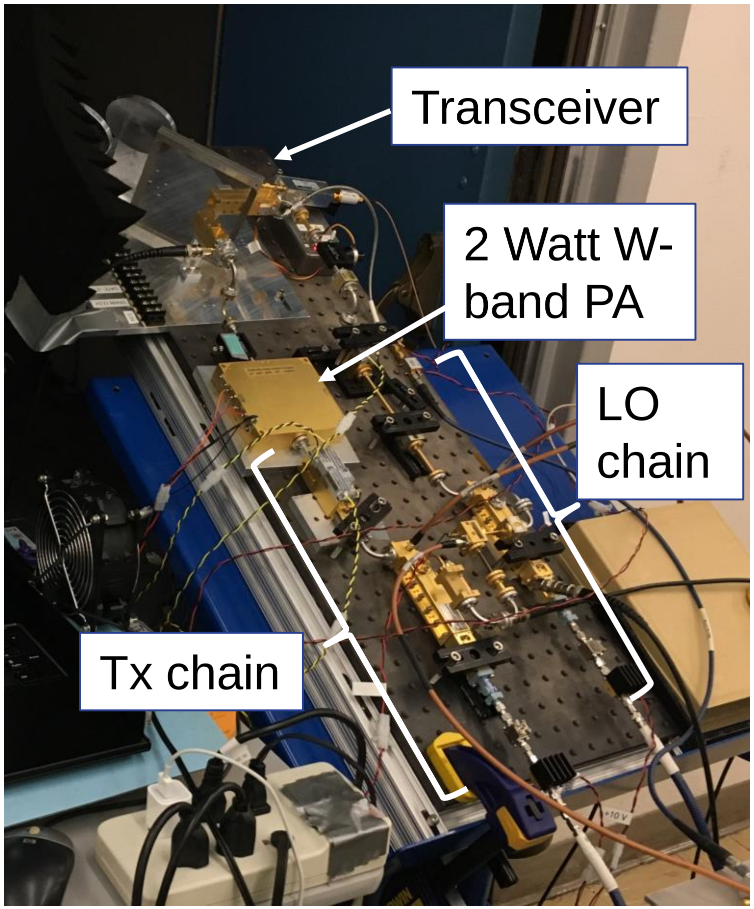
VIPR architecture

- Transmitter tunable from 167 to 174.8 GHz
- Nominal range resolution 2.5 m (60 MHz chirp bandwidth)
- Very high quasi-optical isolation permits simultaneous operation of Tx/Rx **and** single common aperture
- Oscillator phase-noise cancellation (homodyne) techniques enable thermal-noise-limited detection

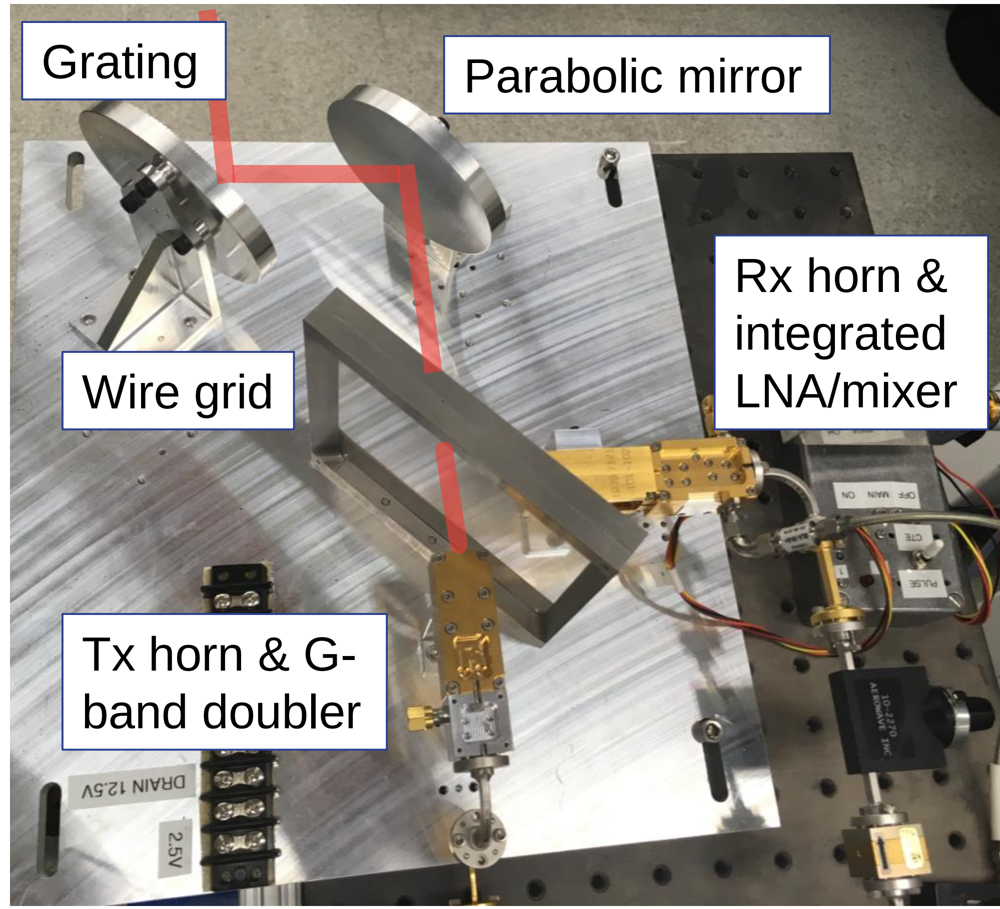


Ground testing setup

Radar front end



Transceiver



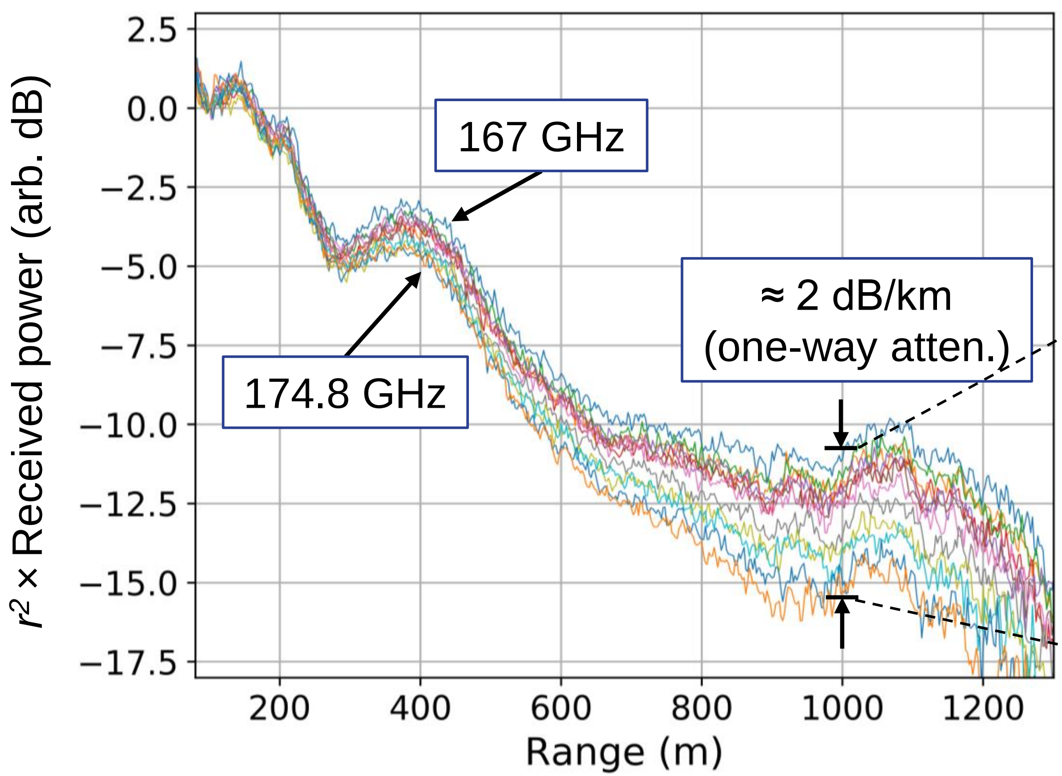
- 100 mW Tx power
- 40 dB antenna gain

Values for initial testing

Rain/cloud field tests @ JPL

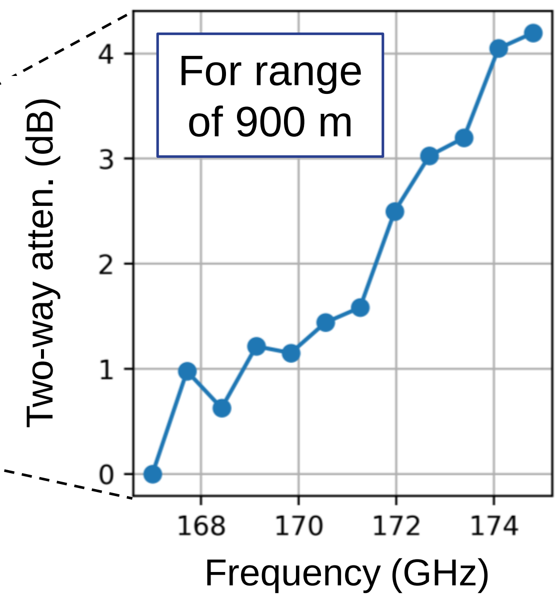
Precipitating clouds

Power spectra normalized to values at 100 m



Reflectivity

$$r^2 P_e(r,f) \propto Z(r) e^{-2\alpha(r,f)}$$



Background noise floor considerations

- Differential measurement derived from ratio of *radar echo power* at two different ranges:

$$\frac{P_e(r_2,f)}{P_e(r_1,f)} \propto e^{-2\alpha(r_1,r_2,f)}, \quad \alpha(r_1,r_2,f) \propto \int_{r_1}^{r_2} \rho(r')dr'$$

One-way optical depth

- But the power we detect is the sum of the echo power *plus* the background noise power:

$$P_d(r,f) = P_e(r,f) + P_n(r,f)$$

- Note:

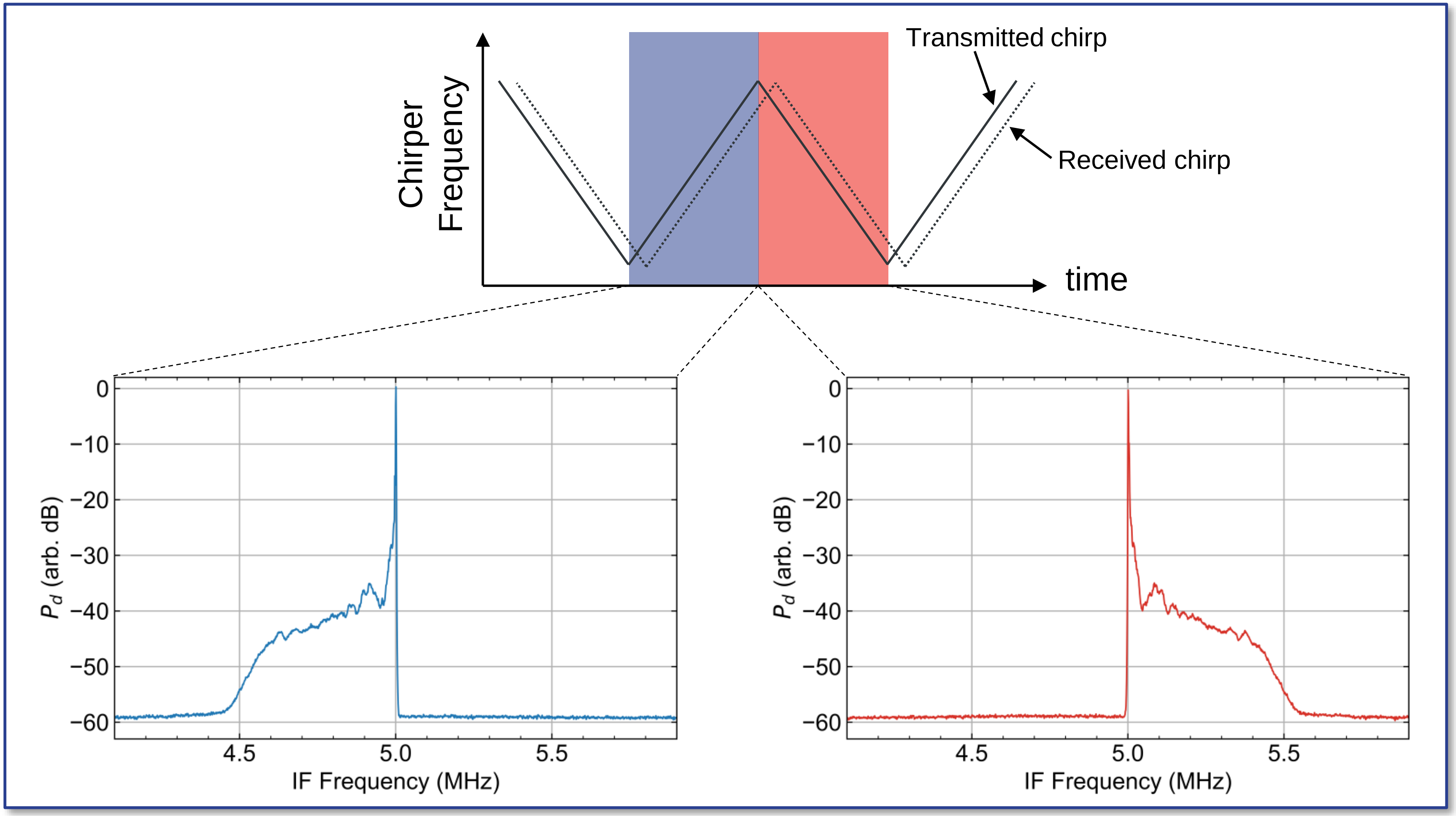
$$P_n(r,f) \neq \text{constant}$$

  - Ripple in the radar IF spectrum
  - Changing scene brightness temperature

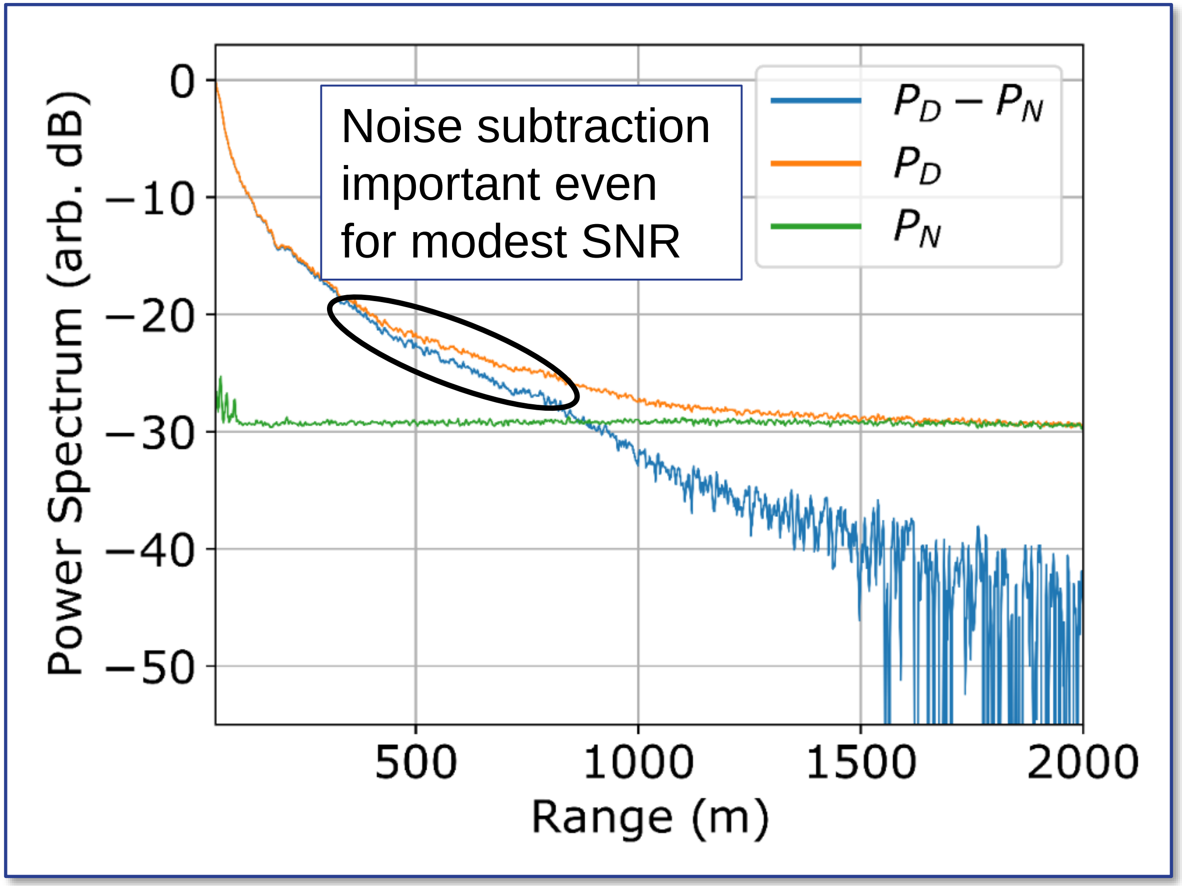
⇒ have to acquire and subtract true background noise floor – otherwise clear low-humidity bias for low-SNR

Real-time noise floor subtraction

— Acquire cloud/rain signal spectrum **and** background noise floor simultaneously by using bidirectional chirp (triangle wave)

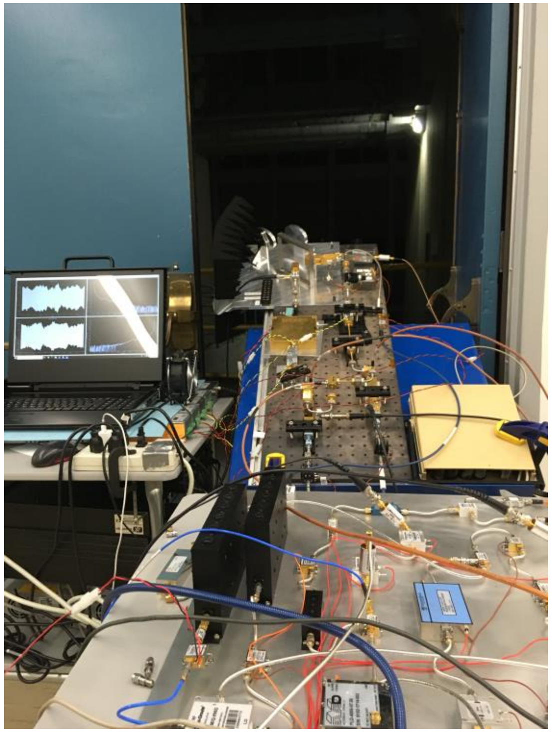


Background noise floor considerations

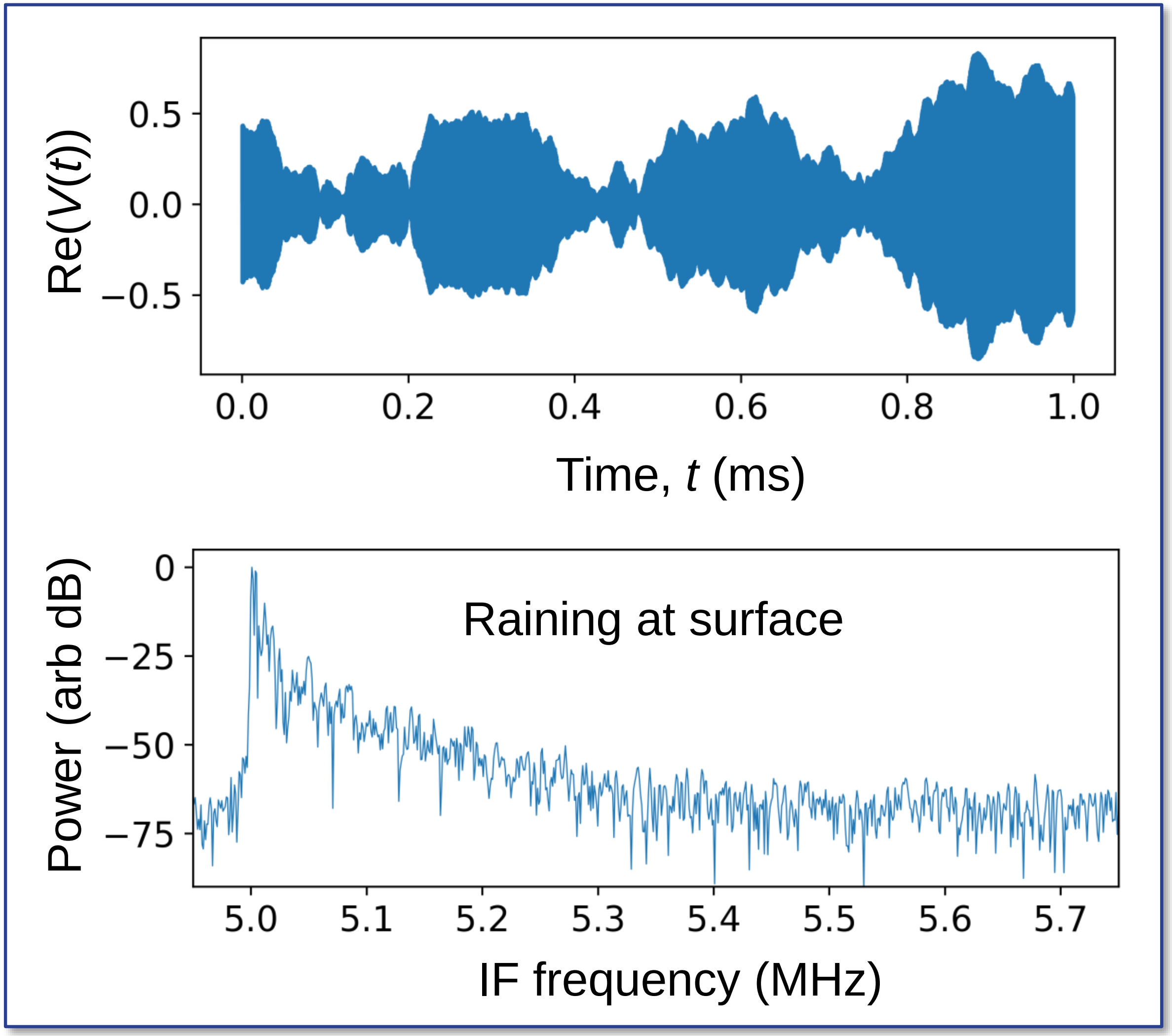


Rain/cloud field tests @ JPL

- Radar pointing 30° above horizontal
- N = 2000 chirps (1 ms) at each of 12 Tx frequencies
- Total meas. time = 25 sec



Downwards chirp



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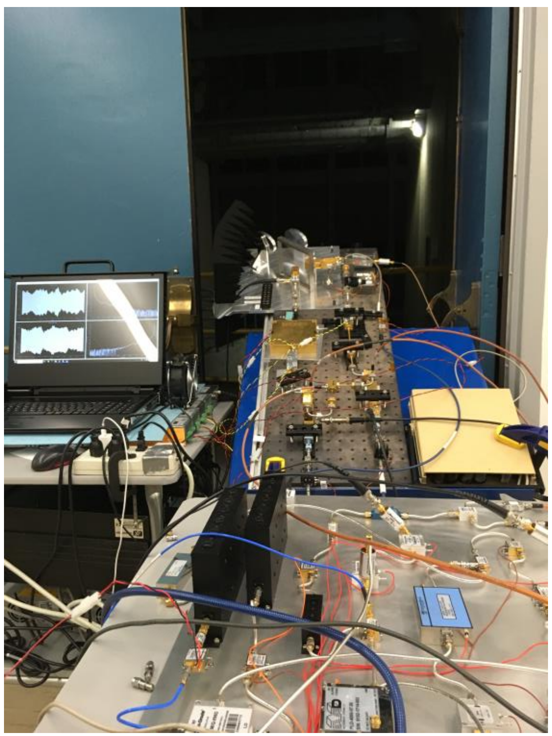
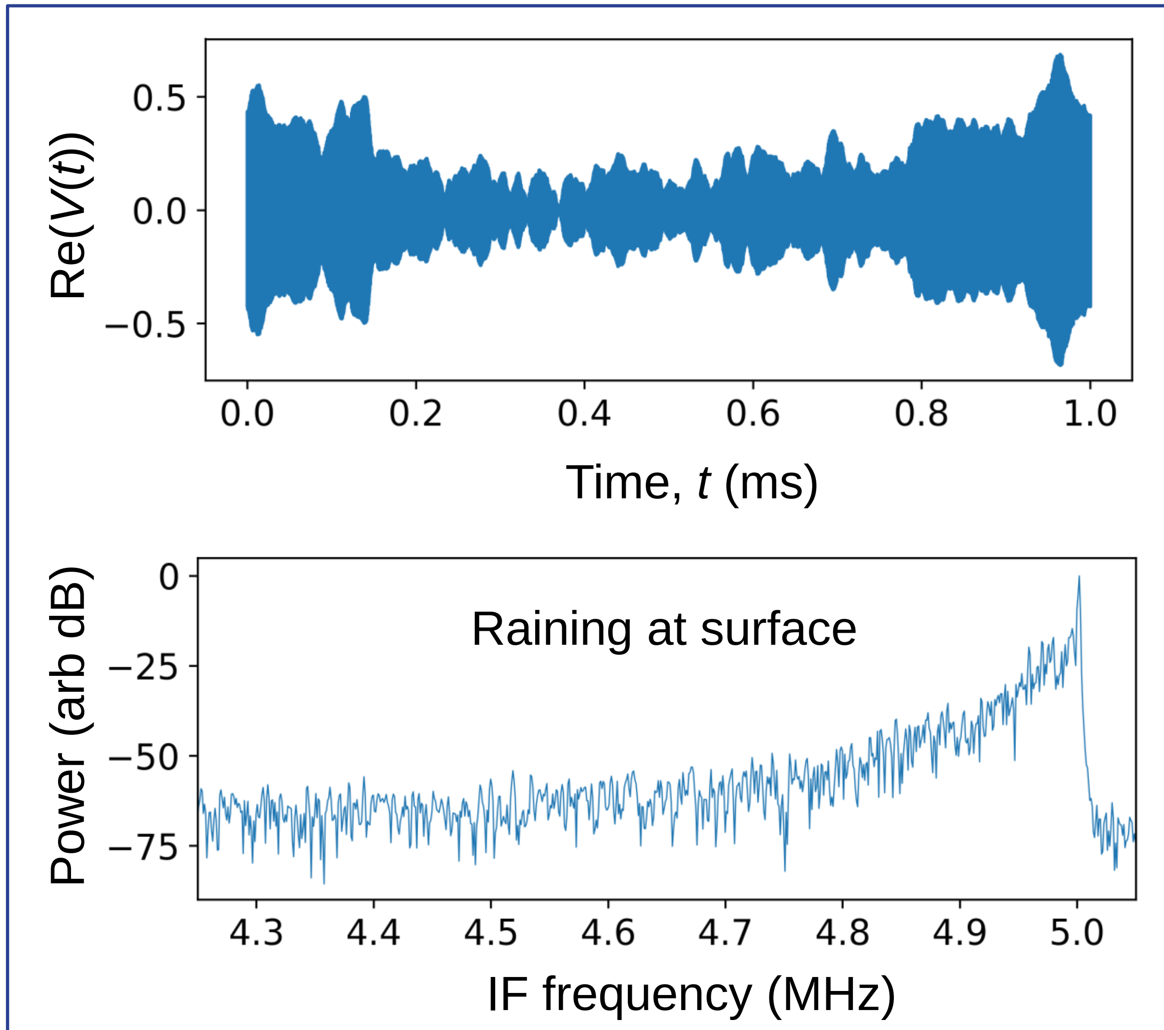
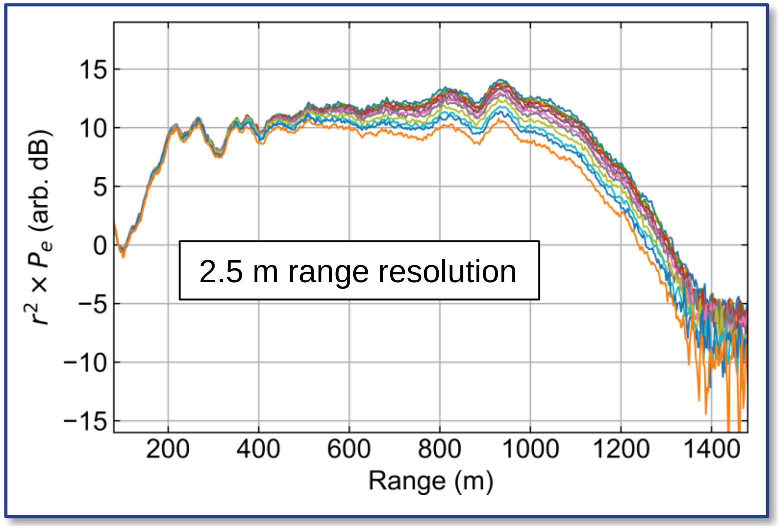


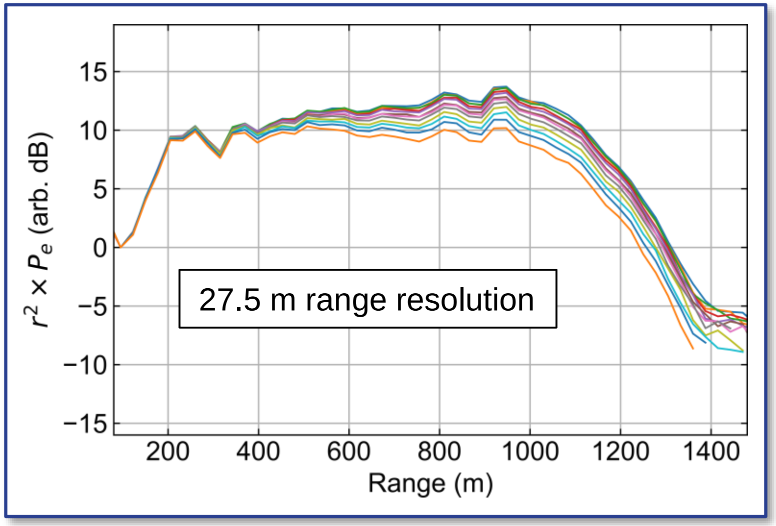
Upwards chirp



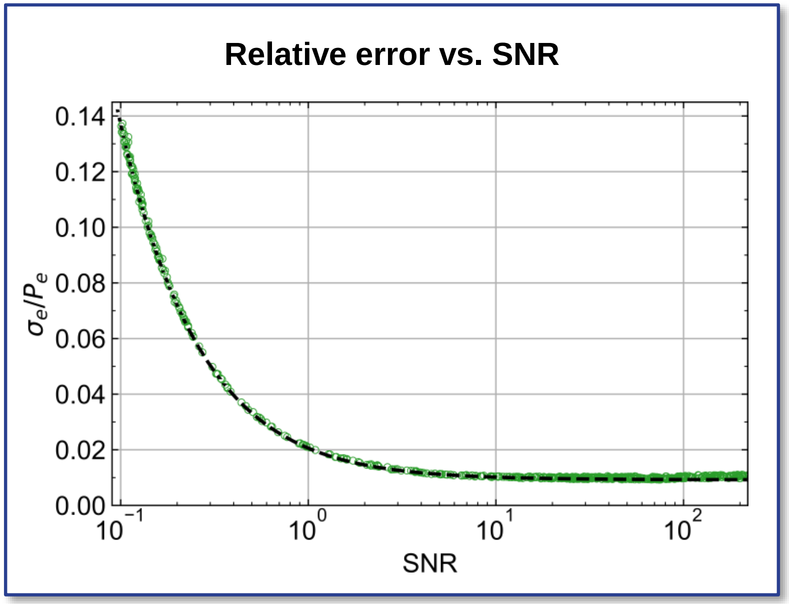
DAR signal processing



Bin (i.e. downsample) radar spectra by factor of 10 to reduce statistical uncertainty



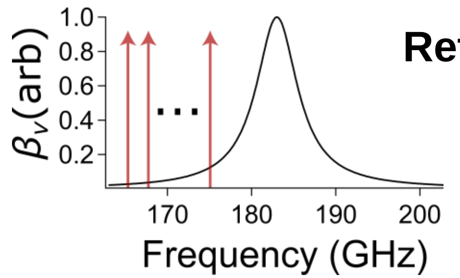
- Measurement error agrees very well with statistical model based on radar speckle noise



R. Roy *et al.*, Atmos. Meas. Tech. Discuss., in review (2018)

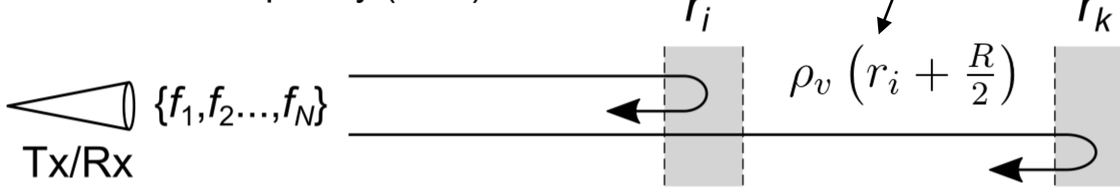
Humidity retrieval

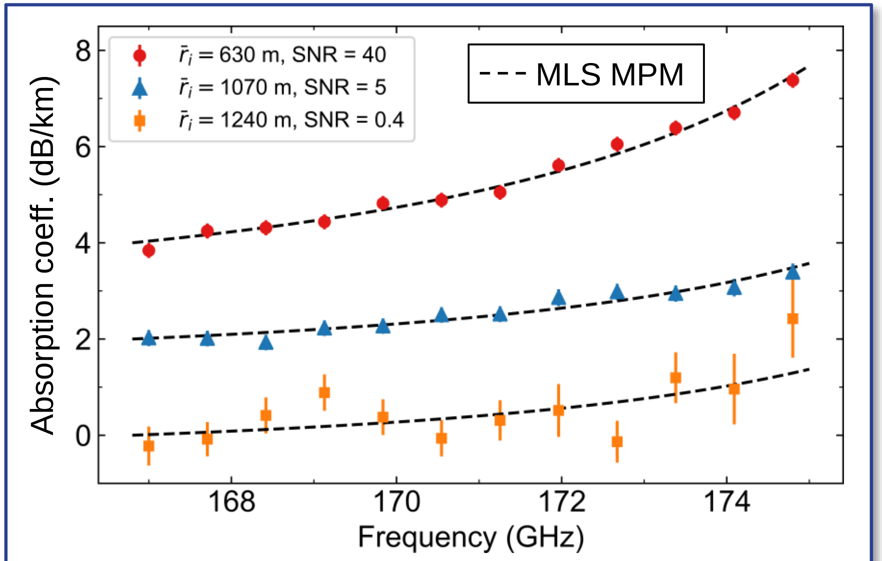
- Fit millimeter-wave propagation model to measured absorption coefficient $\beta_v(f)$ to extract humidity

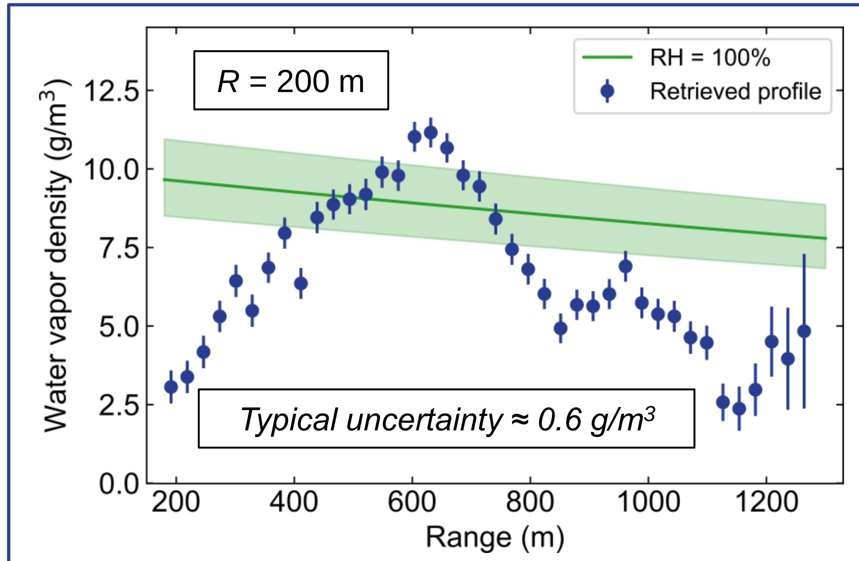


Retrieval step size: $r_k - r_i = R$

$$\beta_{\text{meas}} = \frac{-1}{2R} \ln\left(\frac{P_e(r_i + R, f)}{P_e(r_i, f)}\right)$$

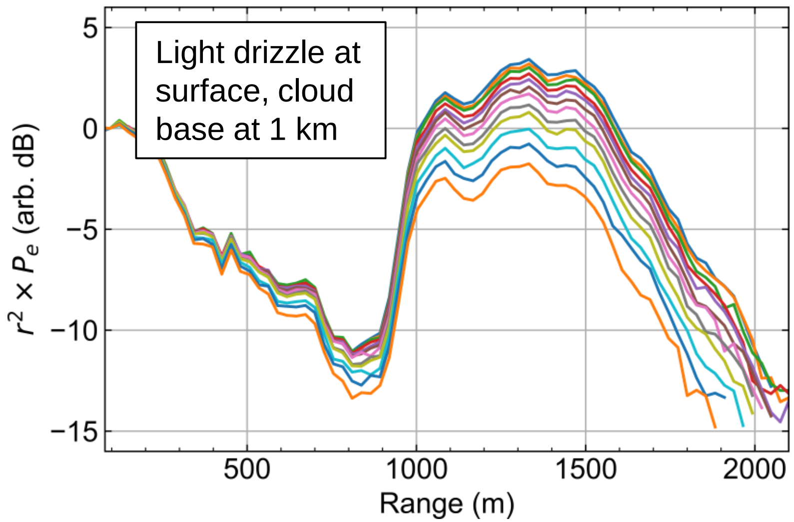


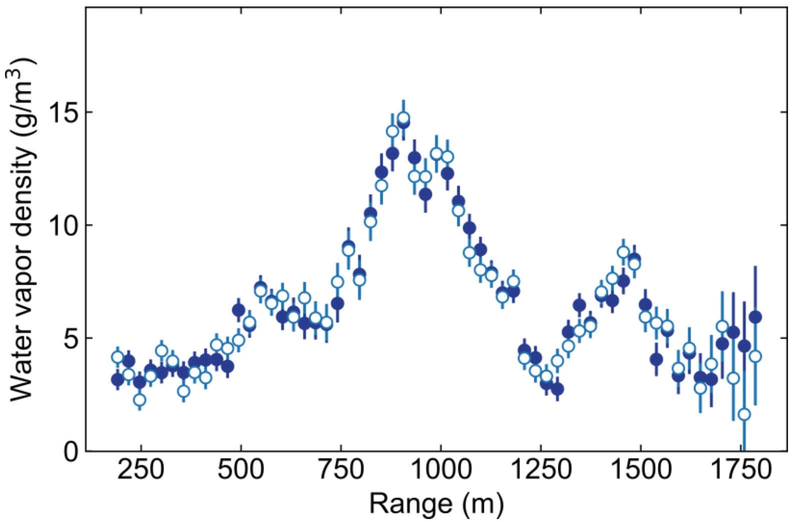


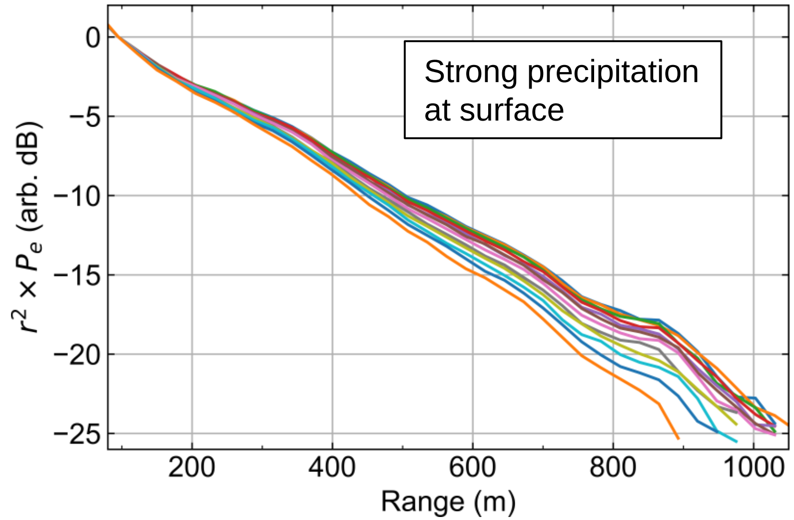


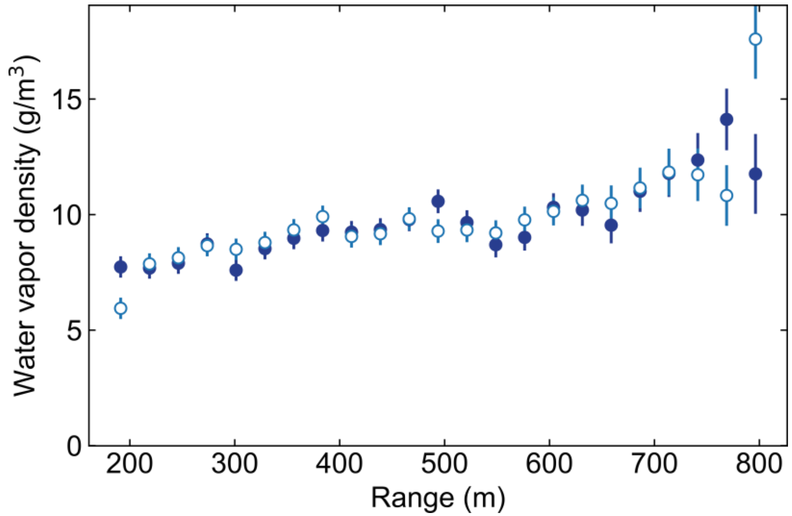
R. Roy *et al.*, Atmos. Meas. Tech. Discuss., in review (2018)

Measurement reproducibility



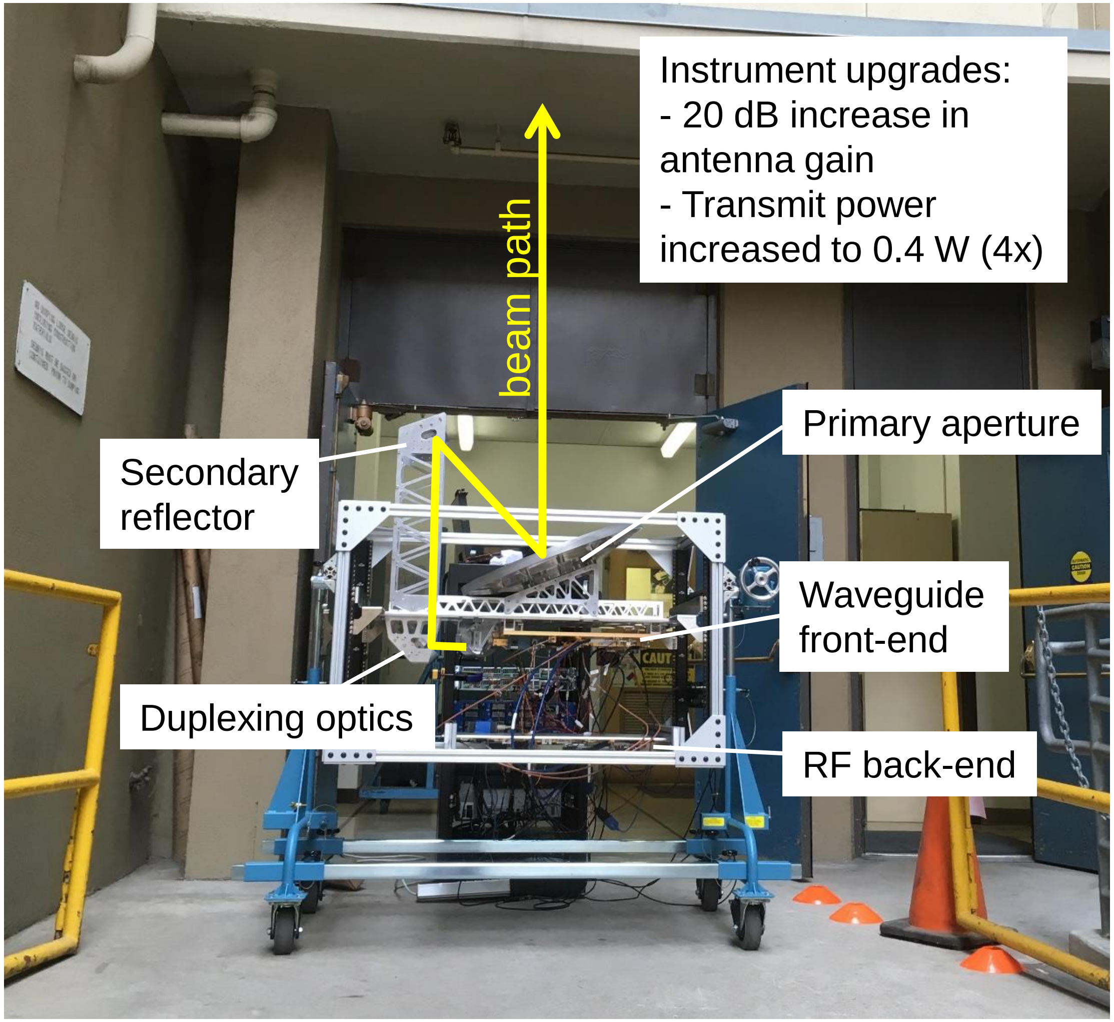


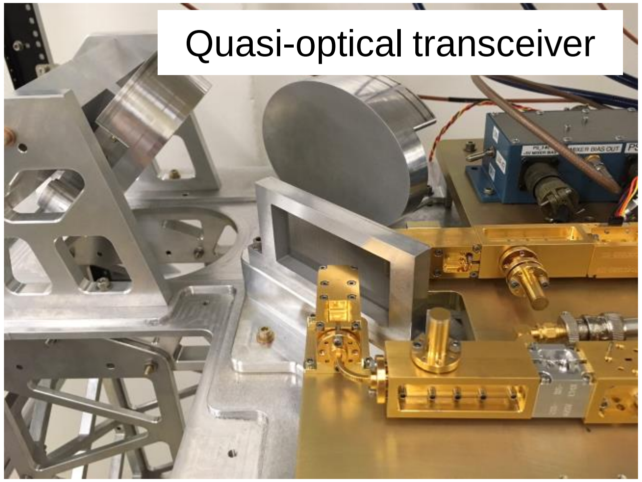


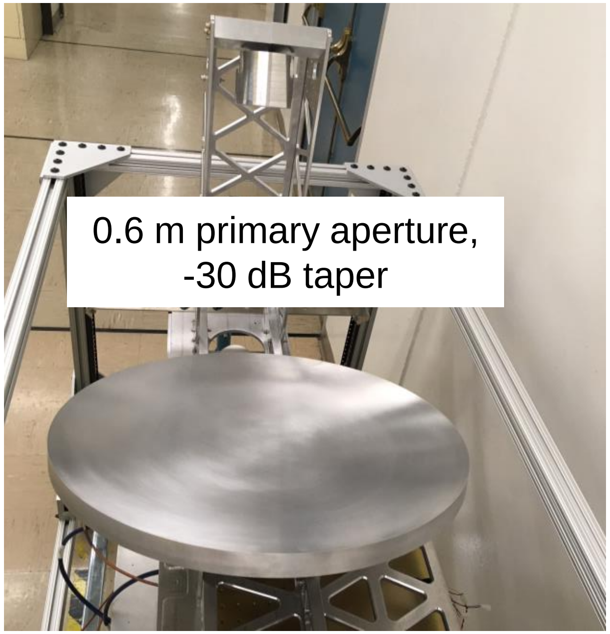


Toward airborne deployment

Airborne compatible VIPR system on Flotron rotation stage

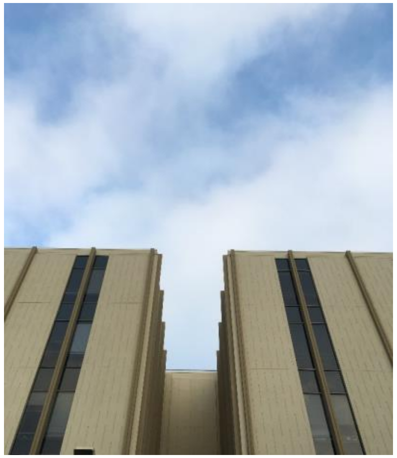


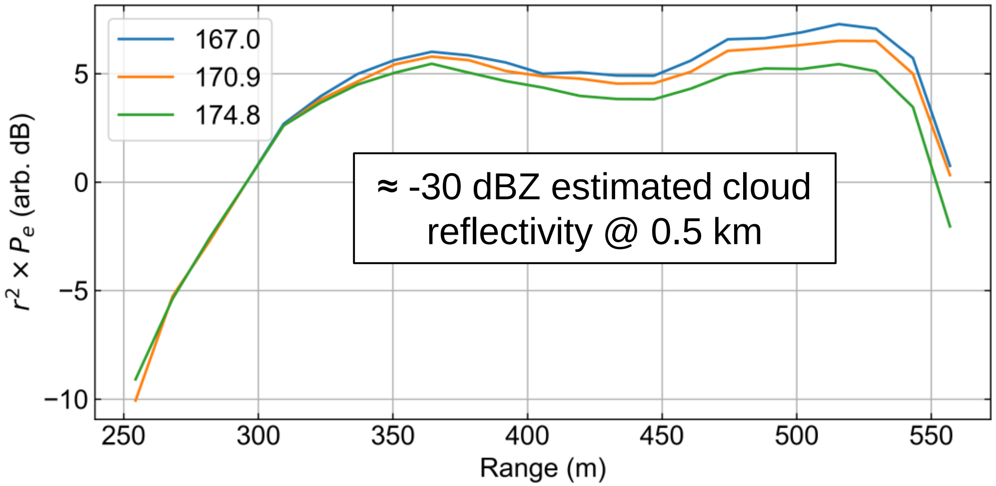




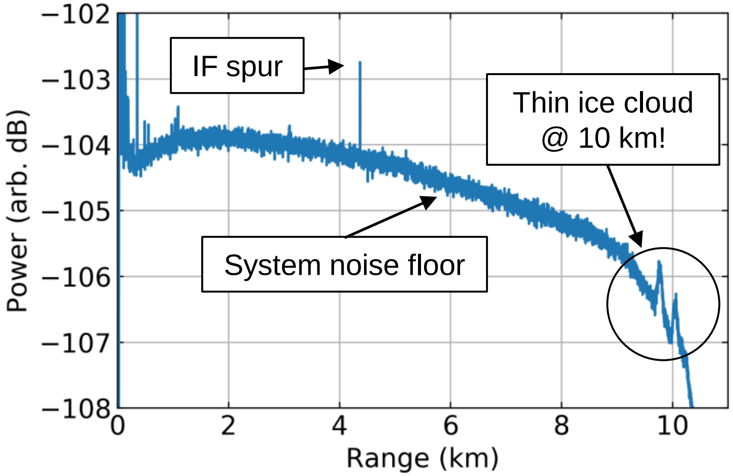
Preliminary tests of new system

Morning low, tenuous clouds





Ground-based detection of upper-tropospheric ice cloud



This is the world's first G-band atmospheric radar

Conclusions and outlook

The present:

- G-Band differential absorption radar proof-of-concept instrument assembled and preliminary field testing successful
- First ever remotely sensed measurements of range-resolved humidity within clouds presented (*R. Roy et al., Atmos. Meas. Tech. Discuss., in review*)
- Signal processing and humidity inversion algorithms demonstrated
- Aircraft compatible architecture assembled and commencement of ground testing

The future:

- Field testing with coincident radiosonde measurements for instrument validation
- Testing from an airborne platform – investigate surface returns for total column water retrieval

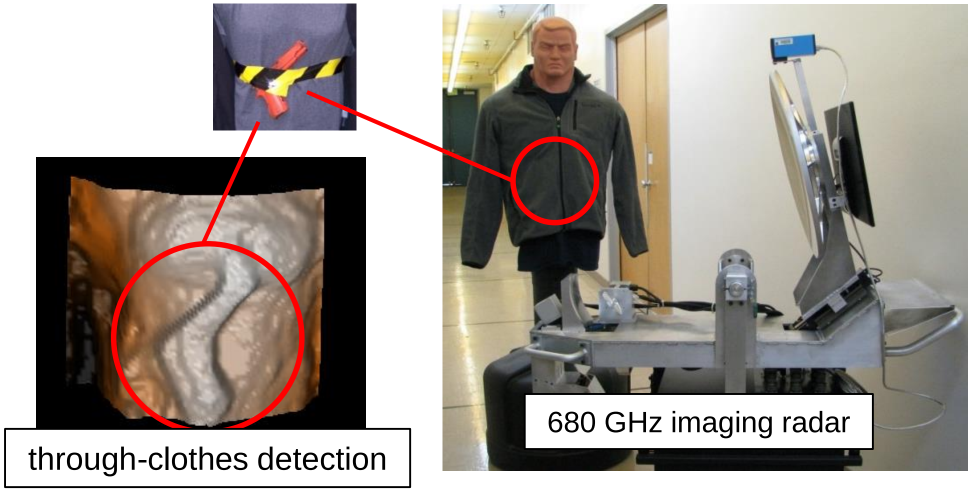
We are grateful to NASA's Earth Science Technology Office for supporting this project through the Instrument Incubator Program.

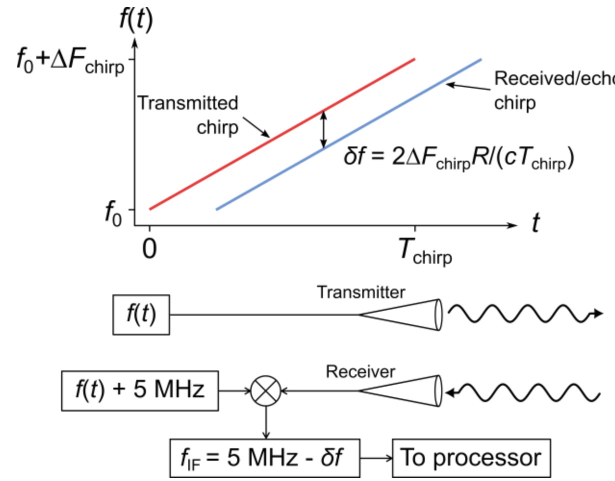
Thank you for your attention

Questions?

Instrument heritage at JPL

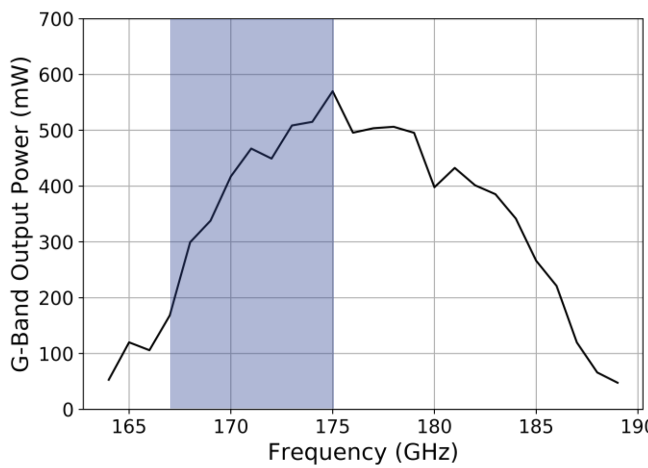
Frequency-modulated continuous-wave (FMCW) radar for security imaging

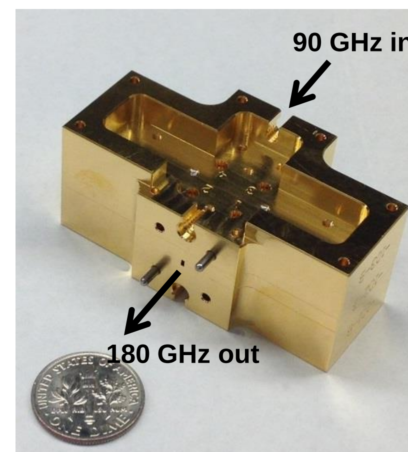




- Extensive THz FMCW radar R&D for security imaging applications
- NASA funded effort for high-power solid-state sources near 183 GHz (ESTO ACT-13)
- State-of-the-art InP low-noise amplifiers developed for millimeter-wave radiometry and heterodyne spectroscopy

High output power G-band sources





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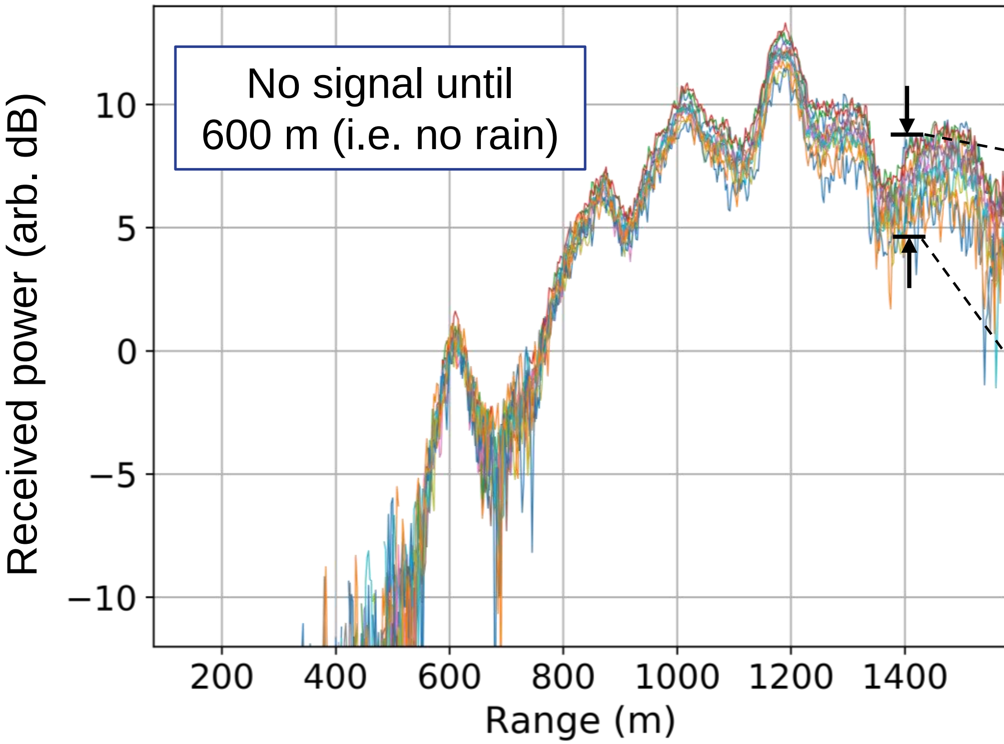
Rain/cloud field tests @ JPL

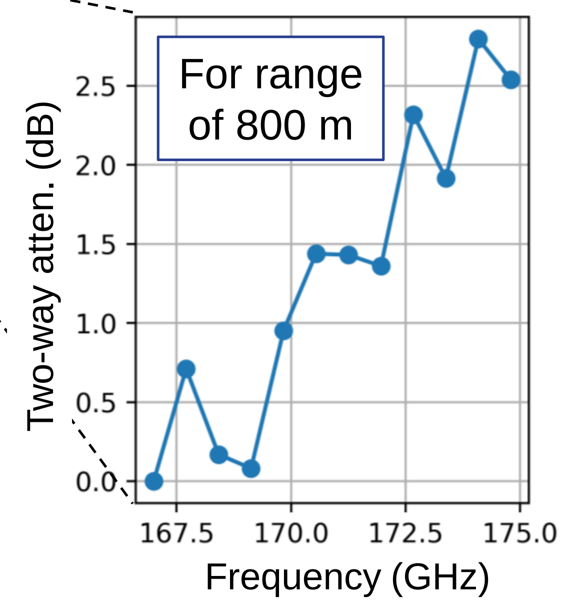
Non-precipitating clouds

Power spectra normalized to values at 600 m



Reflectivity

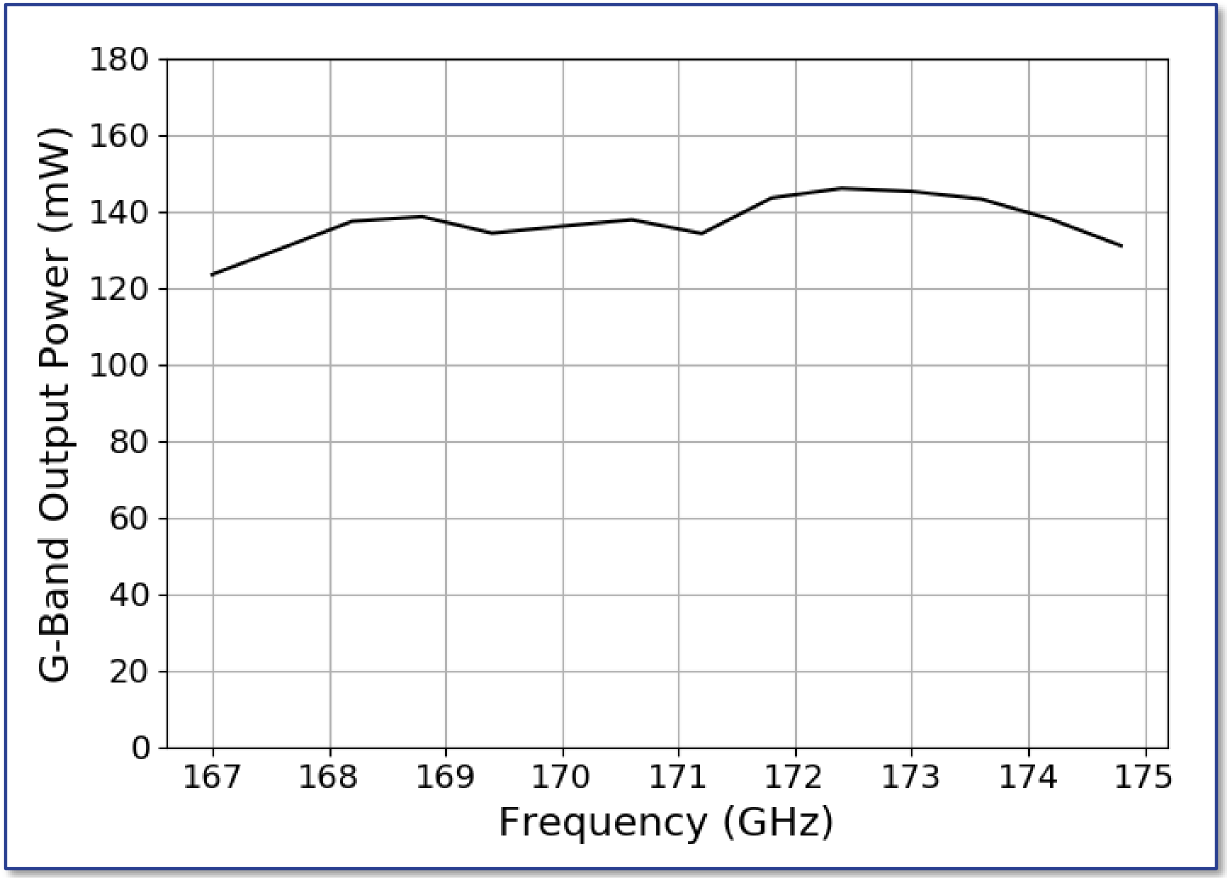
$$r^2 P_e(r,f) \propto Z(r) e^{-2\alpha(r,f)}$$



G-band transmitter

Single G-band frequency doubler (used in ground testing presented here):

- ~400 mW W-band input
- ~30% efficiency



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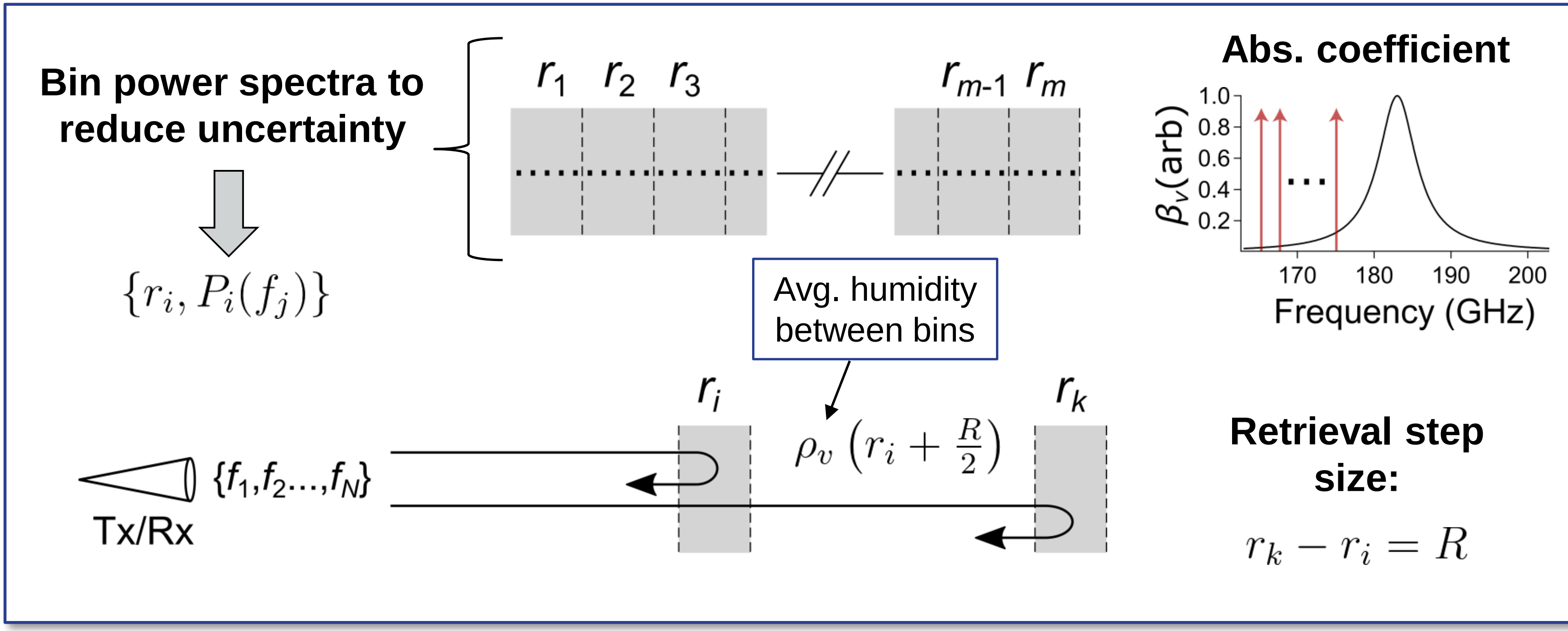
Humidity retrieval



Retrieval algorithm:

Average N_p pulses for N frequencies, subtract noise floors, and bin resulting spectra to obtain $\{r_i, P_i(f_j)\}$

→

For each r_i, calculate

$$\ln\left(\frac{P_k(f_j)}{P_i(f_j)}\right)$$

and fit known dependence β_v(f) to measurements

→

Returns average humidity between each r_i and r_k, and therefore the profile with resolution R